Status and Prospects of the ITER Plasma Physics Experiment. Is it time to terminate the project? Part I

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Abstract

The International Thermonuclear Experimental Reactor, ITER, a huge Tokamak plasma physics apparatus, is under construction since 2007 in Southern France. The ITER project was initiated (around 1985), as a scientific experiment, to find out if nuclear fusion energy could become a technological option for a peaceful and clean electric energy production during the first half of the 21st century.

In part I of this report, the original promises and hopes of the ITER experiment, as presented between 1990 and the year 2000, are confronted with what has been learned so far and especially since construction began some 10 years ago.

For example it was planned that experimentation with 100-200 million degrees Celsius plasma could start about 10 years after the construction would begin. Furthermore, only another 5 years would be required to achieve a substantial several minute net energy production from the deuterium-tritium (DT) nuclear fusion process. Following those promises, the project was funded and began officially in the year 2007. With France being the host country of the project, almost 50% of the 5 billion Euro construction cost was expected to come from the science budget of the European Union. The other participating countries, China, India, Japan, Russia, South Korea, and the USA, agreed to contribute each about 9% to the budget. According to the agreed budget, is was planned that non fusion plasma experiments would start around the year 2019 and that by 2025 significant net energy production could be demonstrated with DT fusion experiments.

However, only a few years after the project received the green light in 2007, the estimated construction cost began to explode and the ITER management had to admit that the original plans could not be realised. The latest 2018 estimates, which include a drastically downscaled experimental program, show that the construction will cost at least some 20 billion Euros. Furthermore, the first basic plasma experiments are also not expected to begin before the end of 2025. It has also been admitted that the ability to demonstrate significant few-minute deuterium-tritium fusion energy release can not be expected before the year 2040.

As those deuterium-tritium results are "Go/ No-Go" criteria for the realisation of nuclear fusion for electric energy production, and for a realistic initial design of a "demonstration reactor", DEMO, which has to be at least three times larger than the ITER, can not begin before the year 2040.

To summarise, the experience gained during the 30 years design and construction process of the ITER Tokamak, demonstrates that **Tokamaks are not the technology which leads to commercially competitive energy production.**

1 Introduction

During the 1950s and 1960s, most prominent scientists, and not only those with expertise in nuclear physics, from all around the planet believed that the energy released in the nuclear fusion of hydrogen isotopes, similar to the processes which power the sun, would become, within at most a few decades, a new energy source. As hydrogen, which can be obtained from water (H_2O), is an essentially unlimited resource, it was hoped that the technology of nuclear fusion energy would not only be cheap, but would also satisfy the energy needs of industrial societies essentially for ever. In addition it was also claimed that this technology, soon to be realised, would allow to produce clean and unlimited energy without CO_2 emissions and also without the unwanted radioactive nuclear fission byproducts.

This widely held belief was likely based on the fact that the concentrated efforts by a group of determined scientists and the military, known as the Manhattan Project, led within only three years to the development and utilisation of the Uranium and Plutonium nuclear fission bombs, which destroyed Hiroshima and Nagasaki in 1945. Within less than 10 years after those devastating fission bombs, even more destructive explosives, based on the nuclear fusion of hydrogen isotopes, were developed first by the US and only shortly afterwards by the Soviet Union [1]. Those new bombs allowed another increase of the explosive power with respect to nuclear fission bombs by a factor of 50-100. In parallel to those destructive efforts, scientists and engineers also started to develop nuclear fission reactors for civilian use and especially for the conversion of the liberated nuclear energy into very concentrated thermal energy. The next and easy step was to convert this energy, like in conventional thermal power plants, into electric energy. Again, the technical realisation of electric energy from nuclear fission, including however many unwanted side effects [2], was realised within only 10 years after the first fission bomb had exploded.

In contrast to those success stories in using nuclear fission energy, the dream of cheap, clean and limitless nuclear fusion energy appears to be as far away as it used to be some 65 years ago. In fact, during those 65 years, several new fundamental obstacles have been identified. An overview can be found for example in [3].

In contrast to what is often claimed, the challenge to reach a stable hundred million degrees Celsius hot plasma state of hydrogen isotopes, required to overcome the electrostatic repulsion of protons[1] is not the only problem.

The invention of the Tokamak technology, [4], opened a path to achieve and to control a hundred million degrees Celsius stable plasma, a mixture of ionised hydrogen nucleons and electrons. This technology was initiated by the physicists I. Tamm and A. Sacharov during the 1950s. The first Tokamak (T-1) began operation in 1958 and the first results were presented around 1965 and published in 1969. This initial success lead to the construction of dozens of Tokamaks all around the planet. As a result of those experiments, higher and higher temperature plasma conditions were managed. Following those "success" stories, it was relatively easy to believe, after the removal of the obstacle to reach temperatures of hundred million degrees Celsius, that the remaining other problems would take at most a few decades to solve. As a result, the involved scientists claimed that the Tokamak technology would lead to the mastering of nuclear hydrogen fusion energy before the end of the 20th century.

However, in reality and only during the last decade of the 20th century some 15 Mega (Million) Joule (less than 5 kWh)[2] were liberated in deuterium-tritium fusion experiments.

[1] It is important to realise that the condition to overcome the electrostatic repulsion in stars, like the sun, is realised and stabilised by the huge gravitational pressure of massive stars.

[2] This amount of fusion energy corresponds only to the energy content of about 1 Kg of dried wood. A really tiny amount when compared with the electric energy produced from todays commercial photovoltaic cells (producing about 200 kWh/m2/year) in Southern Germany and which use the light from the sun, a 150 million km distant natural fusion reactor.

Those results were obtained with the already large, about one hundred m^3 plasma volume Tokamaks, JET (Europe), [5], and the TFTR (US), [6] experiments.

It was already understood during the 1970s, that huge Tokamaks with a plasma volume of a few 1000 m^3, at least a factor of 10 larger than the European JET reactor, would be required to reach stable nuclear fusion conditions with a potential for a net energy gain.

As the costs for such huge experimental Tokamaks would exceed the individual research budget of the US, the European Union and the Soviet Union, the idea of a joint project, ITER (international thermonuclear reactor) was initiated at the 1985 Geneva Meeting of R. Reagan and M. Gorbachev. During the following years, thousands of scientists and engineers from many countries, under the umbrella of the IAEA, contributed to the design of a huge Tokamak. However, their original proposal, with an estimated project cost of about 10 billion dollars, was rejected by the interested countries as being roughly by a factor of two too expensive [7].

After reducing the size of the Tokamak, and the potential power output from 1500 MW to about 500 MW, the construction cost was estimated to be below 5 billion dollars. As a result, the green light to proceed towards the construction of the ITER project was given around the year 2000. After years of ongoing design optimisations and negotiations between the interested countries, Cadarache in Southern France was selected as the construction site and the project officially started in 2007.

The European Union countries and Switzerland agreed to contribute slightly less than 50% of the construction costs, of which 20% comes from France, as the hosting country. The rest of the cost is shared roughly equally between the other participating countries. Those other countries are China, India, Japan, Korea, Russia and the United States, with each contributing about 9% of the total budget. Soon after the project officially started, is was acknowledged that construction costs would be far higher than originally presented. The latest cost estimates given by the ITER management from 2018 are at least 22 billion dollars. However, according to the latest estimates from the USA, the cost would certainly be much higher and could even reach up to 60 billion dollars [8]. In addition, the experimental ITER program, especially the tritium breeding tests, considered to be as essential as the problem to reach stable plasma conditions, has been largely reduced and delayed to keep the budget "under control".

Part I of this report reviews the history, status and prospects of nuclear fusion energy using the Tokamak approach, focusing especially on what has already been learned during the last 10 years during the construction of the global ITER project.

Section 2 presents the evolution of the "science and technology" based roadmaps towards the goal of electric energy producing fusion power plants.

In addition to the apparent failure of the Tokamak approach to master nuclear fusion, several other fundamental problems for commercial nuclear fusion for peaceful energy production are presented. As those problems can not even be studied with the ITER project, they are only summarised in section 3 of this report. However, as those problems seem to provide an explanation of why commercial nuclear fusion for electric energy production will always be an energy source of the future (e.g. that will never be realised!), a more detailed analysis of those obstacles will be presented in Part II of this report.

The evolution of the ITER project during the last 20 years will be presented in section 4. In section 5, the significantly reduced experimental potential of the ITER project is discussed and the results presented in this report are summarised in section 6.

The analysis shows, that the potential results, even if from now on the ITER project can finally perform according to the 2018 plans, will not be sufficient to justify the spending of another few 10s of billions of Euros until 2040.

In conclusion, it is found that one has learned already enough from the efforts to construct the ITER Tokamak, to conclude that the Tokamak technology will not be the path that will lead to commercial and competitive nuclear fusion energy on our planet.

In fact, adding the long list of fundamental obstacles, discussed in detail in Part II of this report, and more than 65 years after the realisation of the hydrogen bomb, our knowledge appears already to be large enough to accept that commercial nuclear fusion energy on our planet will always remain an energy source of the future.

It is thus time to begin the process of a peaceful retirement of the ITER project and to accept that the only long term use of nuclear fusion energy on our planet is the indirect usage of the light, which comes from the 150 million km distant natural nuclear fusion reactor called the sun.

2 Roadmaps towards nuclear fusion energy on our planet

The most optimistic scenarios from scientists and engineers working in the fusion environment, are outlined in regular intervals in what is often named as "Roadmaps Towards Fusion Energy". In the following the evolution of this roadmap [9], [10] and [11] within the European Union will be described.

2.0.1 The 1995-1999 Nuclear Fusion Energy roadmap

During the early design phase of the ITER project in the 1990s, a 50 year roadmap towards nuclear fusion produced electric energy was presented and published in June 2000 [9].

This first roadmap assumed a 3 phase Tokamak reactor evolution process, beginning with an ITER like project, would lead within roughly 50 years to nuclear fusion produced electric energy. Accordingly, once the successful DT fusion results from the ITER project were obtained, a roughly 4 times larger demonstration Tokamak reactor (DEMO), with a sustainable long time thermal power production of 2 GW(thermal) and some production of electric energy, could be designed.

The design of DEMO was assumed to be possible once ITER had succeeded in providing net thermal 0.5 GW (500 Mega Watt) power production from DT fusion for several minutes. The authors of those studies estimated that about 10 years would be required for the construction of DEMO and that another 10 years of DT experiments would demonstrate the mastering of DT fusion, the breeding of tritium and the transformation of the nuclear fusion energy into electricity. It was claimed that DEMO would provide sufficient information about DT fusion in Tokamaks and that those results would allow engineers to take over to begin the design of a first commercial Prototype reactor (PROTO) with an electric energy output of some 1.5 GW electric power, (roughly 2-3 times larger than DEMO). It might be interesting to note that this proposed electric power goal corresponded roughly to the electric power of the EPR nuclear fission reactor design during this period. Such a EPR fission reactor has been, since 2007, under construction in Flamanville, France[3].

The fusion science experts claimed that, once the funding agency would give green light for the ITER project, it would take only about 10 years until the experiments could begin. They estimated further that the relevant experimental results could be obtained within the following 5-10 years. According to the roadmap shown in Figure 1 below, and with the start of the ITER project in 2007, the experimental program should be in full speed today (2019). Furthermore, those results should already be usable for the 5 year design period of the DEMO reactor.

The roadmap also presented the minimal experimental program and the goals which must be achieved in each step, before the design of the next Tokamak could begin. For a project like

[3]This fission reactor was imagined to be constructible within 5 years and with a budget of roughly 3.3 billion Euro. The latest estimates have increased the construction cost to 10.9 billion Euro and a start date not earlier than the second quarter of 2020.

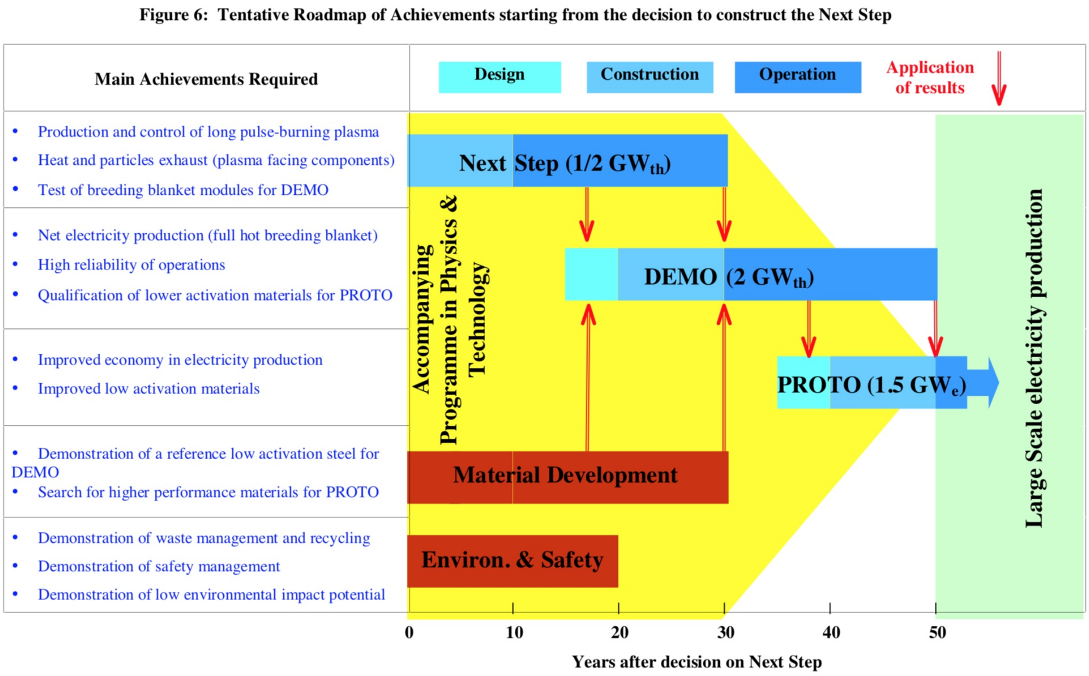

Figure 1: The tentative roadmap towards electric energy from nuclear fusion and from the year 2000 [9].

ITER, it was expected that this experiment will demonstrate:

(1) a several minute long pulse of a DT burning plasma with a thermal nuclear power of 500 MW and with roughly a factor of 10 more thermal energy produced than the electric energy required to heat the plasma;
(2) prove the concept of the heat and particle exhaust system and;
(3) demonstrate that tritium breeding blanket modules, surrounding the $800m^3$ plasma volume of ITER, can be constructed in such a way that the tritium self sufficiency can be guaranteed for the DEMO and PROTO reactors.

The same experts, assuming that the ITER project would proceed easily according to their plans, estimated that the far more complicated DEMO reactor could be constructed again within 10 years. Rather unscientifically, they also could not imagine that any problems, during the next decades and with the ITER and DEMO projects would lead to possible delays of the PROTO program.

Accordingly, PROTO was considered to be the final step before large numbers of huge Tokamaks would be constructed all around the planet.

The PROTO reactor, about 10 times larger than the ITER Tokamak was estimated to be designed and constructed in 5 years and 10 years respectively. Adding those years, and assuming no delays or problems during the next decades, it was claimed that electric energy production would become available in only(?) 50 years (roughly between 2050-2055), after the decision and the financial support for the ITER project was given. It is perhaps important to note that neither this roadmap, nor those subsequent roadmaps presented any construction cost estimates.

Comparing the year 2000 roadmap with todays knowledge about the ITER project, e.g. the 2018 estimates, [12], from the ITER project shows that plasma physics experiments could not begin before December 2025, and that significant results from the Deuterium-Tritium fusion experiments can not be expected before 2040.

As those experimental DT results are required for the design of the DEMO project, it can be stated today that about 20 years and 10s of billions of Euros were required, to demonstrate that the most secure estimates about the ITER project were already wrong by at least 20 years.

While this first "50 year" roadmap program looked somewhat ambitious, but still like a rational approach about what needs to be experimentally shown, already at the end of the year 2001 [13], it was succeeded by a new timeline. This "Fast Track Expert Meeting" concluded that the time scale towards electric energy production could be shortened considerably. Those experts claimed that it would be possible to combine the DEMO and PROTO reactor generations into a single one, and accepting that this new DEMO like Tokamak would "not yet be fully technically and economically optimised". However, this approach would shorten the previous 50 year timescale to electric energy production by 15-20 years.

The 2001 meeting resulted in the mandate for a "Fusion Fast Track Working Group", with the clear goal of outlining how energy production could be achieved within only 30-35 years.

In October 2008, a report about the R&D Needs and the "Required Facilities for the Development of Fusion as an Energy Source" was published by the European Commission for Research and the Directorate of Euratom [14].

According to those experts, it was stated in the 2008 report that:

- *"The assessment is based on the programme' s objective to achieve the ultimate goal of enabling the entry of fusion into the commercial regime in a fast track approach with the creation of prototype reactors in approximately 30 or 35 years."*
- *"The Panel was deeply impressed by the progress achieved in fusion R&D, the scientific-technical quality of the work being undertaken, the sharing of tasks among the partners and the commitment of all parties in the Programme towards achieving the goal of useful fusion power."*
- *"The Panel is impressed by the quality of the research community and the coherence of the programme, and supports its thrust for a rapid and efficient development towards the ultimate objective."*

Those statements sound rather strange when knowing about the ITER realities, cost explosions and delays since 2007. Unfortunately, the same incorrect methods and assumptions, likely with a large input from the experts which wrote the previous roadmaps, are continued to be used so far in the subsequent roadmaps which were published until 2018.

Those roadmaps towards fusion energy production do not appear to represent the scientific understanding at the time of publishing, and they also do not include (a) reflections about the experience gained since the previous roadmaps were published and (b) do not contain explanations why past roadmaps could not be realised. Consequently, the scientific expertise of those involved is in doubt.

2.1 Expectations from the 2012 Roadmap and the 2018 Roadmap

Following a request by the European Commission at the beginning of 2012, a new roadmap, "Towards Fusion Electricity by 2050", was published in November 2012 by the The European Fusion Development Agreement (EFDA).

This report was written during 2012, some 5 years after the ITER construction had begun. During the time of writing, it was already known that the originally promised construction and experimental goals could not be achieved. It was also known that the construction costs had already exceeded the promised 5 billion Euro budget by at least a factor of 2-3. Nevertheless, the 2012 Roadmap presented severals goals, during three periods which are:

- 2014-2020: *Construct ITER within scope, schedule and cost;*
- 2021-2030: *Exploit ITER up to its maximum performance and prepare DEMO construction; several pressing problems are mentioned in this report.*
- 2031-2050: *Complete the ITER exploitation; construct and operate DEMO.*

Only a few years later, the reality of the ITER project has proven those roadmap statements completely wrong.

Furthermore, almost unnoticeable for most outside observers, the cost explosions of the ITER construction resulted also in a downscaling of the most important DT experiments. Among those dropped programs, one finds that the DT fusion experiments can not begin before the year 2035. Perhaps even more important is the dropping of a detailed testing of Li-blankets, supposed to cover the few 1000 m^3 plasma volume, and considered to be essential for the design of a future Tokamak reactor.

It can only be concluded that the scientists participating in the writing of the 2012 roadmap, ignored for whatever reasons, the facts and presented totally outdated and unrealistic goals. One also might find it surprising that the funding agencies and their scientific advisors also voluntarily ignored reality, when following the ideas presented in the 2012 Roadmap uncritically and uncritically continued the funding of the ITER project.

Another roadmap was published in September 2018 by the Eurofusion group (which has replaced the EDFA in 2013). Finally one might hope that the past project delays would be explained and those new insight would influence the imagined possible timeline of electric energy production from nuclear fusion.

Unfortunately, the 2018 report is essentially silent about the reasons why the past experimental goals and the costs estimate were totally unrealistic. However, it is at least mentioned in the preface of the 2018 roadmap that the experimental ITER results, which were considered to be mandatory before the design of the DEMO Tokamak could begin, will now not be available if the roadmap for fusion electric energy by 2050 has to be kept.

Accordingly one finds the following statements in the 2018 version:

"The programme to implement this strategy involves designing DEMO while ITER is in its construction and early operation phase, before it has reached its ultimate performance goals."
and

"However, DEMO takes advantage of the science, technology and engineering advances and knowledge already being developed for ITER. Naturally, its final design can be adapted following ITER results."

Perhaps the most significant part from the 2018 Roadmap is the new timeline figure shown below. Overall, the figure looks rather similar to the ones from previous roadmaps. However one observes that all quantifiable "measurable" milestone dates have been dropped. Apparently, the authors do not believe themselves in any reliability of their own projections anymore.

In summary, past roadmaps demonstrated a total failure to outline realistic time and budget scales for the ITER construction and the time scale of its future experimentation. As a consequence, the expertise of those scientists working in and for the nuclear fusion environment appears to be highly questionable.

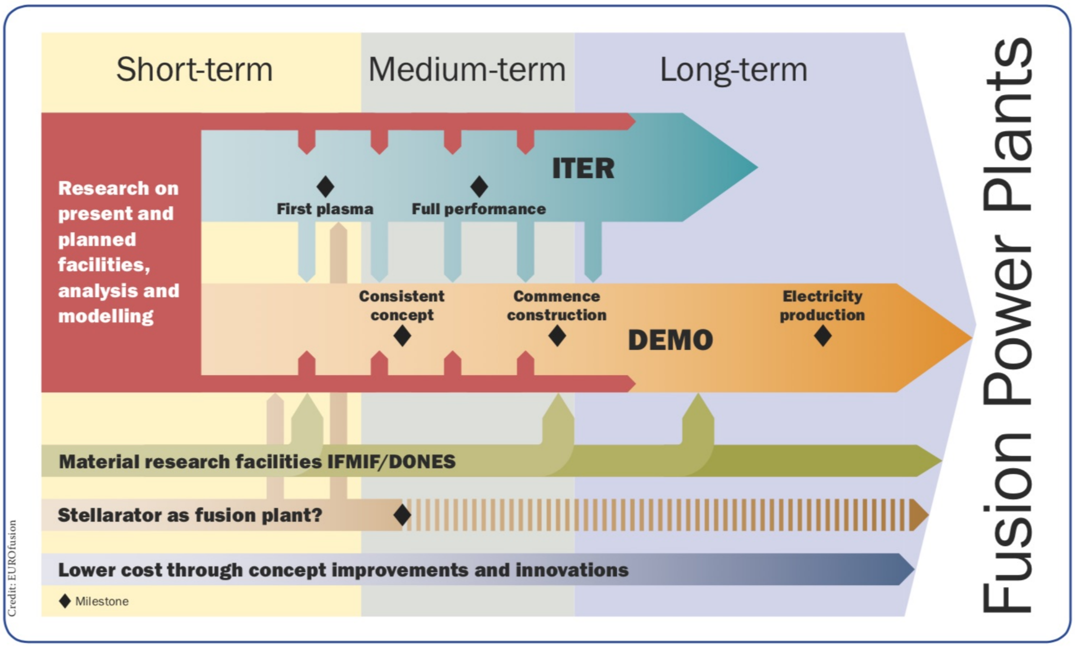

Figure 1: The European Roadmap in a nutshell: The specific challenges will be introduced in Section 3 and then further described in Section 4. Research on present-day devices, as well as theory and modelling, give input to ITER and (possibly via ITER) to DEMO. For clarity not all interrelations are included (for example the stellarator line will provide input to ITER scenarios).

Figure 2: The tentative roadmap towards electric energy from nuclear fusion and from the year 2018 [11]. It should be noted that, in contrast to previous versions, the time axis is shown without any quantifiable milestone years.

3 The remaining problems of controlled nuclear fusion energy on our planet

The process of nuclear fusion of hydrogen isotopes, as the energy source of stars, was understood already during the 1930s. The very strong nuclear force, which binds protons and neutrons, has roughly a range corresponding to the size of these particles. As a result most bound states of protons and neutrons[4] have a slightly lower mass than the sum of the separated protons and neutrons. According to Einstein's famous formula ($E = m \times c^2$) large amounts of energy are liberated in the nuclear fusion of protons and neutrons.

The electrostatic repulsion of two positively charged protons (and other hydrogen isotopes), acting over larger distances, can be overcome if their kinetic energy is large enough to allow that the hydrogen isotopes can come close enough that the attracting nuclear force dominates.

In stars the repulsion is overcome by the gravitational pressure from their huge mass. This option does not exist on our planet, and temperatures of more than 100 million degrees Celsius are needed to give sufficient kinetic energy to the hydrogen isotopes. Such temperatures and the subsequent nuclear fusion of hydrogen isotopes can be reached during the explosion of nuclear fission bombs. Obviously, the destructive energy release of such explosions excludes the use of this method for electric energy production.

Generations of scientists and engineers have worked on this problem and came up with great ideas to first split the electrons from the neutral hydrogen atoms at relatively modest temperatures of several thousand degrees Celsius, resulting in a so called "plasma", a gas like

[4] Unbound neutrons have a short lifetime of some 10 minutes and do not exist in sizeable quantities in the environment

state of positively charged hydrogen isotopes and the negatively charged electrons. Electromagnetic waves enable further heating and million degrees Celsius plasma temperatures could be obtained. In addition, it was rather obvious that "material containers" with melting temperatures of at most a few thousand degrees Celsius could not be developed to keep the plasma close enough together. However, it was found that special configuration of magnetic fields, acting like magnetic bottles, can confine the plasma for a long time.

While several magnetic field configurations were tried, especially the invention of the Tokamak magnetic field configuration, originally invented by scientists from the Soviet Union, allowed to reach plasma temperatures of millions of degrees Celsius. Following this idea, the size of this magnetic bottle required for a significant nuclear fusion power release could be easily estimated to be a few hundred to thousands m^3 plasma volume. As a result, engineers and scientists managed to successfully construct larger and larger Tokamaks and reached plasma temperatures of millions of degrees Celsius. It turned out that the construction costs of such experimental Tokamaks was too large even for the most affluent countries and the ITER Tokamak project was initiated as a global nuclear fusion experiment.

Those lobbying for the funding of the Tokamak presented the problem of creating a stable plasma mixture of Deuterium-Tritium at more than 100 million degrees Celsius as the most complicated obstacle to manage nuclear fusion for electric energy production on our planet.

Unfortunately, several other major scientific problems, which are hindering the use of nuclear fusion energy, were omitted and appear to be almost largely forgotten today. Among those fundamental problems, [3], which are likely even more important than the creation of a stable 150 million degrees Celsius plasma, one finds:

- No significant tritium sources exist beyond the needs from the relatively small scale DT fusion experiments at ITER. This is different for a future energy producing fusion reactor, which has to be tritium self sufficient and thus has to breed significantly more tritium isotopes than fusioned in the DT fusion process. Qualitatively, the breeding reaction has to be initiated from interactions of the 14 MeV neutrons, produced in the DT fusion process, with a lithium blanket of significant thickness of perhaps 50-100 cm, which surrounds the few 1000 m^3 plasma area. So far, even the most optimistic simulations failed to find such a suitable material.

- No physical mechanism, which shows how the energy from the 14 MeV neutrons can be transferred in the few thousand m^3 material surrounding the plasma zone to some liquid, has so far been presented.

- There is no material known which can survive simultaneously (1) some chaotic plasma eruptions and (2) at the same time can stand the damage from the extremely damaging neutron flux. There is also no significant intense neutron source, where such materials can be tested for Tokamak fusion like conditions.

- There is no chemical and mechanical process which achieves an almost 100% tritium extraction efficiency from the several hundred tons of lithium in the breeding zone and at the same time avoids chemical reactions of the hydrogen atoms (chemical identical with a tritium nucleus) and the lithium and other surrounding materials.

Those fundamental obstacles might explain why the realisation of nuclear fusion power for cheap and abundant electric energy production, will always require at least another 50 years of research and development and hundreds of billions of Euros from the research budget of many countries.

A more detailed presentation of those problems is clearly beyond the scope of part I of this report. As those problems need to become known and understood by a broader audience, a more detailed discussion of those problems and their current scientific understanding will be presented in Part II of this report.

In any case, it seems obvious that all those problems require scientifically convincing answers from those "experts" lobbying for a nuclear fusion energy on our planet. Until those answers are provided, it does not make sense to invest many more billions of taxpayers' Euros into the continuation of the ITER project and in fact for any related "nuclear fusion illusion" projects.

4 The diminishing goals of the ITER project

As will be presented in the following, the latest (2018) understanding of the experimental ITER goals can be found on the project website[15]. They represent at best only a small fraction of what has been claimed to be possible when the project was proposed in 1997.

According to the scientific consensus in the 1990s, the goals achievable with the original ITER project, imagined to be constructible with about 10 billion dollars, were ambitious, but necessary to understand if Tokamaks could lead the production of electric energy during the first half of the 21st century.

However, no agreement about the financing of the project could be found by the different contributing countries and the scientists and engineers had to go back to the design phase and propose a downsized Tokamak version with a maximum price tag for its construction of 5 billion dollars. Consequently some of the important experimental questions, which according to the scientific consensus were essential, had to be given up.

Still, the "expert" scientists within the global fusion community considered those new goals to be sufficient for the understanding if Tokamaks could eventually lead to the production of electric energy. As a result, the funding agencies in the participating countries gave the green light to proceed with the project. Knowing today that the costs to realise this significantly reduced ITER project have already exploded to more than 20 billion Euros, it is obvious that the assumed costs and the associated experimental goals of the original two times larger Tokamak project were unscientific and totally unrealistic.

In the following it is described how the potential experimental program has changed during the last 30 years. It is shown that the 2018 version of this program has little to do with the original program, which gave the justification for the 5 billion dollar investment.

Section 4.1 summarises the 1990 and 1997 Deuterium-Tritium nuclear fusion results from the European JET Tokamak and from the roughly twin sized US TFTR Tokamak version which can be considered to be the basis for the ITER program. This will be followed (section 4.2) with the main goals proposed for the original project and the ones from the reduced, and in 2007 accepted essentially global ITER project (section 4.3).

Shortly after the construction of the "real" ITER project has started, construction costs exploded and the ITER management was forced to propose a further experimental downscaling combined with significant time delays for the experimentation.

As will be detailed in section 4.4, the latest 2018 evolution of those remaining experiments, combined with at least four times higher costs, requires that the original agreement about the 5 billion dollar project is reanalysed. In fact, those changes of the original experimental ITER program might perhaps already be considered as a failure of the project, as defined in the original agreements signed by the different parties. Consequently there might be no legal obligation to continue the funding.

It sounds reasonable that really independent scientists, with a background in many fields, should investigate the apparent mismanagement of the public funding during the past decade. Only after the results from such an analysis, new negotiations between all participating countries about the future of this project should begin. In order to prepare for such new negotiations, it appears to be useful to prepare a plan B for the additional cost and timescale for an earlier retirement of the ITER project. Those costs could then be compared with the costs to continue the project until 2040 and the costs to terminate it after that date.

4.1 JET/TFTR DT Fusion results (1990-1997)

Experimentation at the European JET Tokamak laboratory in Culham (UK) and its roughly twin size US Tokamak (TFTR) laboratory in Princeton between 1994 and 1997 achieved the first fusion of Deuterium-Tritium isotopes. Both experiments were roughly 10 times smaller than the actual ITER project and achieved some nuclear fusion power, as indicated in the Figure below.

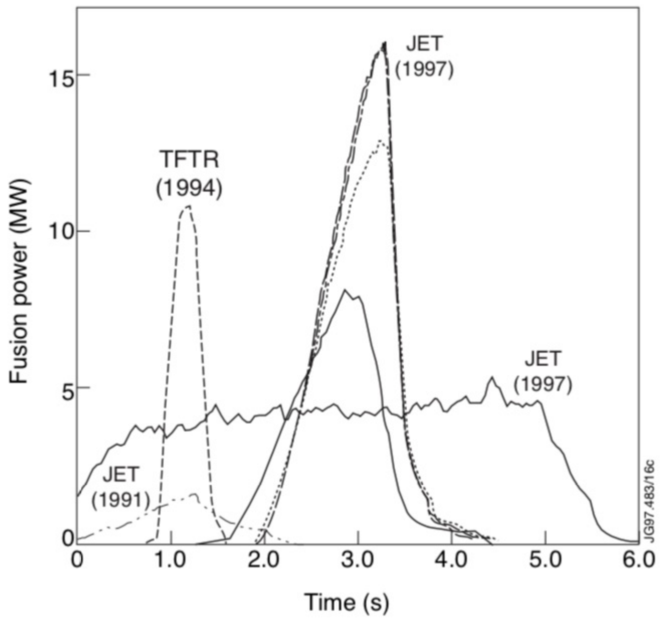

Fig. 16: Fusion power development in JET (1991 and 1997) and TFTR (1994).

Figure 3: The Figure is taken from a 1999 paper by the the former JET director, M. Keilhacker, [16]. It is perhaps interesting to note that the JET group required 6 years, after the very first DT fusion results, to obtain the second and third slightly larger and longer DT fusion signals and that no particular reasons were given for the surprising low experimental activities with tritium.

The signals from the 1997 experiment from the Deuterium-Tritium fusion produced a 15 Million Watt peak power (for 1 second) and 4 Million Watt (for about 5 seconds) correspond to about 15-20 Million Joule of nuclear fusion energy. However, an electric heating power of at least some 50 Million Watt and during a considerable longer experimental plasma heating time was required to achieve those results.

It is important to know that the 18 MeV energy release in each fusion reaction is released in the non relativistic kinetic energy of roughly a 14 MeV neutron and a 4 MeV helium nucleus (α)[5]. Accordingly, the 15 Million Watt peak power production signal, achieved for 1 second, corresponds to about 5×10^{18} DT nuclear fusion reactions. While this seems to be a huge

[5] With 1 eV being the equivalent of 1.6×10^{-19} Joule, the kinetic energy of the neutron corresponds to about 1.4×10^{-12}) Joule.

achievement, it should be noted that this amount of released energy is tiny in comparison to a modern nuclear fission plant with an electric nominal power of about 1500 Million Watt (with a thermal energy of roughly 4500 Million Watt) which is produced continuously during weeks and months and not only during a handful of seconds. Nevertheless, the results from both experiments are usually considered to be important milestones towards the realisation of commercial energy production from nuclear fusion and have certainly been relevant for the funding of the ITER project under construction today.

It should also be noted that those experiments, performed between 1990 and 1997, missed "break even" for DT fusion reactions by at least a factor 5-10. A goal that was explicitly claimed to be achievable in the 1976 management plan for the TFTR project [17]. The "break even" is defined optimistically as the point when the ratio of the total kinetic energy released from the DT fusion divided by the required input heating power to bring the plasma to a temperature of about 200 million degrees Celsius is equal or larger than one. In other words, the released energy from those DT fusion experiments, and counted in the most optimistic way, was significantly smaller than the electric energy put into the system. In addition it should be stated that the Tokamak geometry prevents that the kinetic energy of the 14 MeV neutrons, which are emitted essentially isotropically from the huge plasma volume, can be measured by some significant heating within the plasma surrounding material.

4.2 The 1997 design of the original 10 billion Euro ITER project

Following the results from the JET and the TFTR experiments in Europe and the US, it was concluded that further progress to eventually break even fusion conditions required plasma volumes roughly 10-20 times larger than the one in the JET and TFTR Tokamaks.

The original 1997 ITER design project, [18], had a plasma volume roughly 15 times larger than the JET Tokamak. According to the IAEA document from around 1998, the design corresponded to a magnet configuration of 5.7 and 12.5 Tesla and for a major and minor radius of 8.1 m and 2.8 m respectively and with a plasma heating power of 100 Mega Watt. In comparison the JET Tokamak major and minor radius were 2.96 m and 1.25 m and had a 3.45 Tesla magnetic field.

The goal of this design was to achieve a total fusion power of 1500 MWatt, about 100 times larger than at JET and with a Q value (the ratio of produced fusion energy/electric heating power input) of at least 10. Furthermore, experimental answers for the following problems and their experimental feasibility were considered necessary before the design phase of the next even larger Tokamaks (DEMO and PROTO) could be started.

- Plasma Performance:
  Extended burn in inductively driven plasmas at $Q \geq 10$ for a range of scenarios;
  aim at demonstrating steady-state through current drive at $Q \geq 5$;
  and controlled ignition not excluded. This should be achieved with an input electric heating power of about 100 Mega Watt and reaching such stable fusion conditions for at least 1000 seconds (and perhaps reaching even 6000 seconds).

- Engineering Performance and Testing:
  Demonstrate availability and integration of essential fusion technologies;
  test components for a future reactor;
  and test tritium breeding module concepts.

The costs for the construction and operation of such a project were estimated to be about 10 billion dollars equivalent. The project was considered to exceed the combined science budgets, allocated for fusion research, from the interested countries. The involved scientists and engineers were sent back to downsize a Tokamak project, still consistent with the scientific goals, but for a total budget of at most 5 billion dollars.

4.3 The goals of the 5 billion Euro ITER project

Around the year 2000, a new downscaled ITER project was presented and the goals of the project were defined in the ITER EDA agreement from 2002, [19], as:

"the overall programmatic objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes."

and this should be achieved with

"a minimum cost aimed at a target of approximately 50% of the direct capital cost of the [1998 ITER] design with reduced detailed technical objectives, which would still satisfy the overall programmatic objective of ITER."

It might be important to consider the statement from the scientist within the Special Working Group in their proposed revised ITER design that:

"preliminary studies ... suggest that the direct capital costs of ITER can be reduced significantly by targeting the less demanding performance objectives recommended..."
and that in their view

"these less demanding performance objectives will satisfy the overall programmatic objectives of the ITER Agreement".

The remaining goals of the downscaled ITER project were:

(1) demonstrate a ratio of DT fusion power to auxiliary heating power of at least 10 for a range of operating scenarios for 300-500 sec; and
(2) with a duration sufficient to achieve stationary conditions of 500 Mega Watt and for at least 1000 seconds and potentially up to 3600 seconds. This should be achieved with a slightly reduced major and minor radius of 6.2 m and 2.0 m, corresponding to a plasma volume of 837 m^3 and plasma surface of 678 m^2 and an installed electric heating power of 73 Mega Watt (later extendable to 110 Mega Watt).

Furthermore, this ITER design shall incorporate features that permit to:

- demonstrate the reliability of nuclear components;
- furnish data for comparing candidate concepts for nuclear components and to provide a basis of extrapolation;
- demonstrate tritium breeding;
- provide fusion materials testing data.

During the initial DT Phase it was foreseen to install 421 modules of the first wall tritium breeding blanket.

A detailed construction timeline of this project was presented, and accordingly it would take 96 months (8 years) after the licence for construction was granted to begin the experimental period.

The timeline for the experimental scenario (from the IAEA Document, [19]) is reproduced in Figure 4.

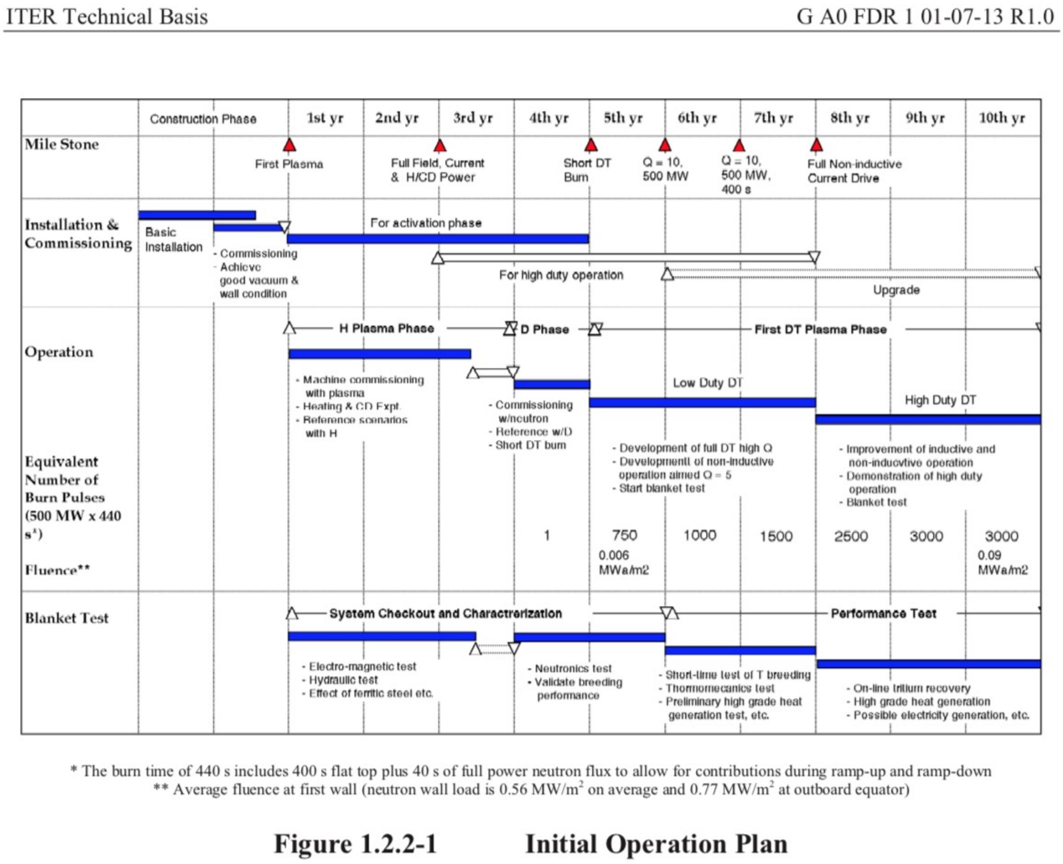

Figure 4: The expected 10 year ITER operation scenario, reproduced from the 2002 IAEA document [19].

Once the construction license was given, it was assumed that construction time for this project would take about 8 years (96 months) until the first plasma experiments could start. According to this plan it would only take an additional 4 years to start the first DT short burn experiment. During the fifth year the experiments would achieve a 500 MW fusion power with a Q value of 10 and already during the next year such pulses would be 400 seconds long and the start of the tritium breeding blanket program could begin.

The project cost estimates, in dollar equivalents[6], were presented in a detailed table (1.9.5-1). The costs were estimated as about 3 billion dollar for the construction, another 2 billion dollars for the planned 10 year experimental program and another 335 million dollars for the decommissioning costs.

This report from 2002 was concluded with:

"Nine years of intensive joint work by the ITER Joint Central Team and Home Teams of the four Parties (three after 1999) under the auspices of the IAEA have yielded a mature design supported by a body of validating physics and technology R&D, safety and environmental analyses and industrial costing studies. The ITER design meets all detailed objectives set by the ITER Parties, with margins in physics and technology to allow for uncertainties, whilst

[6]Around the year 2000 the conversion factor from dollar to Euro was about 1.5. However, perhaps it is more realistic to use todays conversion factor which is close to 1.

satisfying a cost target that makes possible for participants to benefit from the sharing of costs and the pooling of expertise that joint implementation allows."

and

"The ITER co-operation, in combination with the continuing general progress in fusion research, has brought its Parties and the world fusion development programme to the point at which they are technically ready and able to proceed to construction, thus bringing to successful fruition the Parties' efforts, investments and aspirations to date. By enabling, in a single device, full exploration of the physics issues as well as proof of principle and testing of key technological features of possible fusion power stations, ITER will provide the integration step necessary to establish scientific and technical feasibility of fusion as an energy source."

When comparing those estimates with the unfolding reality of the ITER project (cost explosions, significant time delays until 2040, and with significant reduction of the remaining potential experimental goals) since it started officially in October 2007, one can only wonder how it was possible that the scientific and financial control institutions accepted the reduced ITER program from 2002 uncritically?

4.4 Learning from the 2007-2019 ITER construction

Following those ITER design documents, it took another few years until by 2005 a suitable construction place was found in Southern France. Another two years were required to obtain the green light from the science funding agencies from the seven ITER Members –China, the European Union, India, Japan, Korea, Russia, and the United States. Accordingly, the EU as a hosting party of the ITER complex, agreed to contribute about 50% of the project cost, while the other six parties accepted to pay approximately 9% each.

The site preparation began in early 2007, and the 24th of October 2007 became the inauguration date. Perhaps following the 2001 roadmap, this date should be taken as the year when the decision to fund the ITER project was given. The financial budget during this year is given in the 2007 annual report as roughly 50 million Euro.

Interestingly enough, the ITER administration and its international council have been rather unclear about a date which might define the year zero of the project.

As it took another 2 years to complete the site preparation and complete the buildings for ITER administrative buildings perhaps 2009 could be considered to be year zero, after already almost 300 million Euro had been spent. Alternatively, one might also consider August 2010, when the excavation for the foundation for the Tokamak construction started, as year zero.

Perhaps the most logical starting date could be the termination of the revised design review, which according to the 2008 annual report, lead to the construction permit in April 2008. Following this approach the year 2018, after a construction time of 10 years, would become the year when the first plasma physics experiments could begin. According to a planned construction time of less than 10 years, the 2008 and 2009 annual reviews of the ITER project, [20], 2018 was presented as the target year for the first plasma experiments. This interval was almost in line with the 2001 initial operation plan, which stated that it would take about 8 years (96 months) to construct the Tokamak.

However, the 2009 annual report (and also the following annual reports until the latest 2017 version) are rather unclear about the definition of first DT experiments. In any case, those experiments were predicted for the years 2025/26 (about seven years after the beginning of the plasma experiments). Those dates indicate already a delay of a few years compared to the initial operation plan, where it was claimed that it would take only 5-6 years after the first plasma experiments to demonstrate a DT fusion power of 500 Mega Watt for about 400 seconds.

During the following years, and until 2018, not only the required construction costs have increased from about 5 billion Euros to now well above 20 billion Euros, but also the earliest possible plasma experimentation dates have been moved to December 2025 (-perhaps it would be more honest to write "during 2026"-) and to 2035 for the beginning of the DT fusion experiments [12].

5 Potential experimentation with ITER (2025-2040)

The latest 400 page version of ITER Research Plan (provisional version), within a "Staged Approach", published in September 2018 [12], outlines the possible experimental plans until 2041. The figure from the report, describing those plans, is reproduced below.

It is useful to highlight that about 5 additional years are associated with "Assembly Phase II, III and IV". Obviously those years, and certainly another couple of billions of Euros, are required to complete the full construction of the ITER Tokamak, as defined in the international agreement for the funding of the project in 2007. Adding those years, the total construction time is currently estimated to be at least 20 years.

It can thus be stated that (1) the promised 10 year construction time was incorrectly estimated by roughly a factor of 2 and (2) that the year 2025, considered now as the termination year of the construction, corresponds only to a fraction of what was claimed possible in 2007; and (3) that huge additional construction costs can be expected from the 5 year assembly phase.

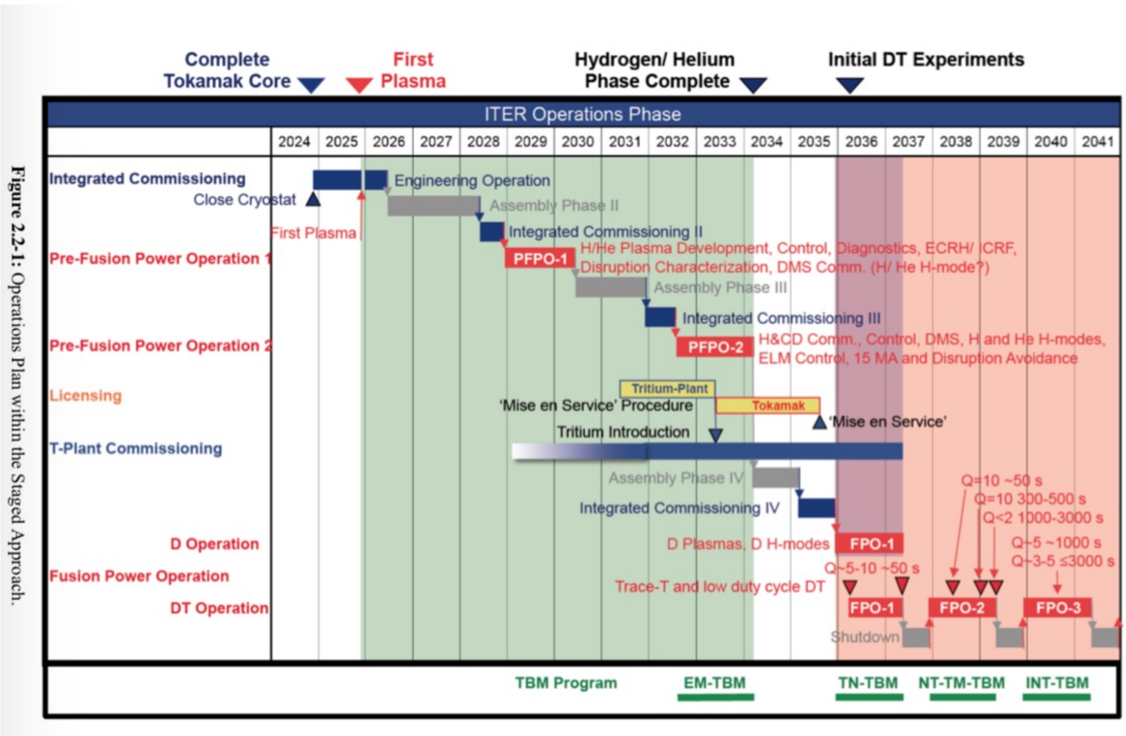

Figure 5: The 2018 provisional operation plan within the staged approach and until the year 2041, reproduced from [12].

Knowing that the outcome of the DT fusion power experiments determine if the Tokamak technology could eventually lead to some electric energy production from nuclear fusion, the current plans for those experiments need to be watched more closely.

According to this 2018 research plan, significant DT fusion power experiments can be expected at earliest during the year 2038, almost 30 years after the ITER construction began and 20 years after this still provisional experimental plan was published[7]. This should be compared to what was described in 2002, as a well understood initial operation program from 2002, and which led to the funding of the ITER project. It was stated that the construction time would be at most 10 years and that it would take 5 years (see Figure 3) to obtain significant DT results. Results from those experiments were considered to be essential to judge if the Tokamak technology could be used to continue the path towards a commercial production of electric energy during the first half of the 21st century.

Perhaps it makes sense to see how such almost unbelievable delays, which document the failure of the ITER goals, are explained in the executive summary of this plan:

This version of the Research Plan is a provisional version of the baseline documentation that has been developed in response to the complete revision of the ITER project schedule within the framework of the Staged Approach, undertaken in 2015 – 2016 and reflects the ITER project strategy as of December 2017.

In other words, the presented plan should not be taken as an accurate planning document as it is based on the highly doubtful assumption that from 2018 on, all construction steps will happen according to schedule.

Only a few lines later, this interpretation is confirmed within the document:

"The Staged Approach foresees First Plasma in December 2025, which is succeeded by a progressive upgrade of the capabilities of the ITER tokamak and facility interleaved with two periods of system commissioning with plasma and experimental plasma studies in H and He plasmas. Completion of construction activities is scheduled for early 2035 and the transition to experiments in D/DT plasmas is planned for December 2035, with trace tritium experiments likely in early 2036 and a gradual transition to fusion power production over the next 12 – 15 months of experimental studies"

It is thus acknowledged that, according to the 2007 definition, ITER will not be constructed by 2025, but that at best it might be completed during the year 2035. Furthermore, the time for initial first DT fusion power experiments, estimated to begin at best in early 2036 are now presented as the beginning of a "gradual" transition from some DT trace plasma experiments, which could lead to some DT fusion power at the end of 2037 and followed by subsequent two-yearly cycles:

"In subsequent experimental campaigns in Deuterium Tritium (DT) plasmas, planned on a two-yearly cycle, the experimental basis for achieving the principal scientific mission goals of the ITER project are developed: a demonstration of Q 10 for burn durations of 300 500 s and the development of long-pulse, non- inductive scenarios aiming at maintaining Q 5 for periods of up to 3000 s.".

It is remarkable that the involved scientists are only now beginning to confess that "the experimental basis for achieving the principal scientific mission goals of the ITER project are developed" after the initial DT experiments, thus at earliest during the year 2037. Perhaps, such statements can be considered as finally replacing wishful thinking with some realism.

[7] So far essentially all Tokamak research plans since the JET and IFTR project began in the 1970s, have proven to be wrong by several years. Accordingly there is no reason to assume that the 2018 "provisional" ITER plans are realistic.

Unfortunately those scientists involved since decades in the project are still failing to admit that their claims, which lead to the funding of ITER some 30 years ago, have not been based on science, but on their wishful thinking to continue plasma physics experimentation at high temperatures.

6 Summary: Tokamaks are not the way towards electric energy from nuclear fusion.

The international ITER (the way to fusion energy) Tokamak, was designed and constructed during the last 25-30 years to demonstrate if this technology could eventually produce significant amounts of electric energy from nuclear fusion of DT isotopes.

This period can thus be taken as a scientifically "hypothesis testing" experiment for the question if the Tokamak technology can be a way to achieve commercially viable electric energy from nuclear fusion during the first half of the 21st century.

For example, and taking the experience gained during the past 20 years of the ITER project as an experimental tests period, one finds that the most advanced theoretical and experimental ideas about the realisation of fusion in Tokamaks have been falsified beyond doubt. In particular it should be noted that:

- Cost estimates have been wrong and increased from about 5 billion Euro to more than 20 billion Euro. This does not even take into account that the currently defined experimental program of the ITER project, and especially the tritium breeding tests, have been significantly decreased during the last years;
- The original 2007 estimates claimed that plasma experimentation would begin around the year 2018 and the vitaly important DT experiments would demonstrate significant DT fusion power between within 1-2 years after DT experiments would start in 2025. Those dates are in contradiction with the latest and still only provisional planning document from 2018. It is stated in this document that relevant plasma experiments can at best begin after another 2 year "assembly phase" (construction) and thus at the beginning of 2028. One can not avoid to conclude that a delay of at least 10 years, after the beginning of the construction some 10 years ago, demonstrates a total failure of the underlying theoretical and experimental understanding which were the basis for the funding of the ITER project. The latest promises for the earliest possible date, which are still very hypothetical, for the first significant DT experimentation have even been further delayed by at least 12-15 years. Furthermore, it is clear that only with positive results from the DT experiments with the ITER project, one can begin to think about the design of an even larger DEMO Tokamak.

Perhaps the most remarkable confirmation about the failure of the ITER project and the associated time and budget schedule came from the December 6, 2017 ITER management press declaration[21]. While the press declaration celebrated (a somewhat undefined) 50% construction milestone of the project, the declaration contained the following remarkable paragraphs:

- ITER scientists predict that (commercial!) fusion plants could start to come on line as soon as 2040. The exact timing, according to fusion experts, will depend on the level of public urgency and political will that translates to financial investment;
- A commercial fusion plant will be designed with a slightly larger plasma chamber, for 10-15 times more electrical power. A 2,000-megawatt fusion electricity plant, for example, would supply 2 million homes.

- The initial capital cost of a 2,000-megawatt fusion plant will be in the range of 10 billion dollar. These capital costs will be offset by extremely low operating costs, negligible fuel costs, and infrequent component replacement costs over the 60-year-plus life of the plant.

Taking those, within a scientific environment rather unusual statements, serious, "ITER scientists" claim that enough information exists already today, and a new and much larger Tokamak, which would produce electric energy, could be constructed already for the year 2040.

This is a remarkable date, as it coincides at best with the date when significant DT fusion results can be obtained from the ITER experimentation and after at least another 10 billion Euros are invested into the construction and likely similar amounts during the potential experimental program.

Taking those words from the official press declaration seriously, the directorship thus claims, "in black and white", that there is no rational to continue the ITER project.

Even for the most optimistic scientifically minded believer in the Tokamak future, those statements from the directorate can only be understood as a sign of incompetence with regards to the real problems of the ITER project and of nuclear fusion energy in general.

Part I of this report can be summarised with the statement: Sufficient information about the design and construction of large Tokamaks has been obtained during the last 20 years, those data allow to conclude that this technology will not lead to electricity producing fusion power during the first half of the 21s century.

In addition, it is difficult to avoid the conclusion that the highly praised "scientific expertise" to control DT nuclear fusion and the related estimated monetary costs, which formed the basis to design the ITER project during the years 1995-2007, were based at best only on gigantic miscalculations.

It seems that only two optimistic options exist to interpret the (experimental) findings presented in this report as:

(1) The hard work of the nuclear fusion scientists from all around the planet, funded during the last 20 years with at least some 20 billion Euros, has experimentally proven beyond doubt that the Tokamak technology will not be the way to liberate fusion energy for the production of electric energy;

or

(2) The claimed scientific understanding of nuclear fusion and its realisation for electric energy production using Tokamaks during the past decades was totally flawed and we finally have learned that it will always take 50 years before electric energy can be produced from the nuclear fusion processes on our planet.

Independent of some potential consequences for the existing control mechanisms for such large scientifically motivated technology projects, and some more philosophical interpretations about the consequences for the future energy use on our planet, it can safely be concluded, that the work for an acceptable termination plan of the ITER project, well before another 10s of billions of Euros are invested into the project, should be initiated now.

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7 conflict of interests

The author states that there is no conflict of interest.

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